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ORIGINAL ARTICLE

How to build a continental scale fireball camera network

Robert M. Howie[1] · **Jonathan Paxman**[1] · **Philip A. Bland**[2] · **Martin C. Towner**[2] · **Martin Cupak**[2] · **Eleanor K. Sansom**[2] · **Hadrien A. R. Devillepoix**[2]

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Abstract The expansion of the Australian Desert Fireball Network has been enabled by the development of a new digital fireball observatory based around a consumer digital camera. The observatories are more practical and much more cost effective than previous solutions whilst retaining high imaging performance. This was made possible through a flexible concurrent design approach, a careful focus on design for manufacture and assembly, and by considering installation and maintenance early in the design process. A new timing technique for long exposure fireball observatories was also developed to remove the need for a separate timing subsystem and data integration from multiple instruments. A liquid crystal shutter is used to modulate light transmittance during the long exposure which embeds a timecode into the fireball images for determining fireball arrival times and velocities. Using these observatories, the Desert Fireball Network has expanded to cover approximately 2.5 million square kilometres (around one third of Australia). The observatory and network design has been validated via the recovery of the Murrili Meteorite in South Australia through a systematic search at the end of 2015 and the calculation of a pre-atmospheric entry orbit. This article presents an overview of the design, implementation and performance of the new fireball observatories.

Keywords Meteors · Meteorites · Fireballs · Bolides · Camera networks · Autonomous observatories · Distributed networks

✉ Robert M. Howie
robert.howie@curtin.edu.au

1 Department of Mechanical Engineering, Curtin University, Perth, Australia

2 Department of Applied Geology, Curtin University, Perth, Australia

1 Introduction

Meteorites provide insight into the formation and current state of the solar system, but the value of most of these (more than 50,000 worldwide) is limited because the origin of the sample, the heliocentric orbit, is unknown. The scientific value of samples with known origins is one of the motivations for sample return missions such as Stardust [1] and Hayabusa [2]. Meteorites with a known pre-atmospheric entry orbit determined by a fireball camera network allow us to constrain the origin of the rock in the main asteroid belt, and possibly in some cases, even the specific asteroid parent body. As of mid 2016, only about 29 [3–8] recovered meteorites have orbits determined through fireball camera networks or other observational means.

Fireball camera networks continuously monitor the night sky for fireballs (meteors magnitude -4 or brighter) produced as larger meteoroids enter the Earth's atmosphere at high speeds (tens of kilometres per second). These larger meteoroids are more likely to produce meteorites on the ground instead of completely burning up during the luminous trajectory (bright flight). The bright fireballs produced during the ablation process can be tracked as they move through the atmosphere using optical means. The observed trajectory (consisting of both position and timing data) allows the calculation of the heliocentric orbit of the meteoroid and a fall position estimate of the meteorite. The fall position must be known with sufficient certainty to recover the meteorite via a ground search, and orbital precision must allow meaningful comparison with the orbits of known Solar System bodies. These constraints inform the observational requirements of a fireball camera network.

The Australian Nullarbor plain is an exemplary site for a fireball camera network due to its dark skies, minimal cloud cover, low rainfall, lack of vegetation and pale geology [9]. The light coloured featureless terrain contrasts well with (usually) black recent meteorites for a visual search. The Australian Desert Fireball Network (DFN) aims to cover the Nullarbor and a significant fraction of the entire Australian Outback with fireball cameras in order to produce the first consistent source of meteorites with orbits (delivering multiple meteorites with orbits per year). The original goal was one million square kilometres of coverage [10], but that has since been revised upwards due to the performance of the new observatories exceeding initial expectations. The new goal is to cover as much good meteorite searching terrain as possible in Australia. The network recovered two meteorites with orbits during its initial phase using large format film cameras (see Section 2.5): Bunburra Rockhole, an anomalous basaltic meteorite [11] in 2008, and Mason Gully, an H5 ordinary chondrite [12, 13] in 2010. A third meteorite (Murrili) has now been recovered using the new digital observatories detailed in this work.

Meteorite recovery rates are determined by network coverage area which is limited by the per observatory cost relative to the imaging performance. Reducing this cost to expand the network is the driving motivation behind the development of a new cost effective fireball observatory for the DFN. The fully autonomous digital observatory (Fig. 1) is designed to record high resolution fireball trajectories in the harsh conditions of the remote Australian Outback and is based on commodity off-the-shelf digital imaging and computing hardware to minimise costs.

Fig. 1 Digtal DFN observatory installation at Mt Ive Station in South Australia

2 Fireball camera networks

The first meteor photograph was captured in 1885 [14], and systematic photographic meteor observations have taken place since 1936 [15]. Three large fireball camera networks with the aim of meteorite recovery were constructed in the latter half of the 20th century. The European Fireball Network (originally the Czechoslovak Fireball Network) and the US Prairie Meteorite Network started operations in the mid ’60’s, and the Canadian Meteorite Observation and Recovery Project (MORP) followed in the early ’70’s [16]. These networks used large format film based camera systems to achieve the required resolution and sensitivity to image fireballs for orbit determination and meteorite recovery. The observatories typically take one exposure per camera per night; an additional exposure is sometimes started after a bright fireball is detected (depending on network capability) [17].

Estimating fall positions of meteorites from fireball data requires camera networks to capture fireball trajectories with high spatial and temporal precision from multiple geographically distinct locations. The spatial precision of the cameras determines the accuracy of the trajectory path triangulation, and relative timing data is required to determine the velocity and deceleration of the meteoroid for mass estimation [18]. Absolute timing (time of appearance) is also required to calculate the pre-atmospheric entry orbit due to the constant orbital motion and rotation of the Earth. Previous networks have employed different approaches to determining absolute timing, ranging from relying on chance observations of the general public (no timing) to high precision sky brightness loggers [16].

2.1 Czechoslovak fireball network

Ondřejov Observatory has a long history of meteor observation, and commenced double station observations using multiple narrow angle meteor cameras in 1951 [19]. These employed a rotating shutter mounted in front of the objective lens to create periodic breaks (at 68 and 98 breaks per second [20]) in the meteor trails created as the shutter arms pass in front of the objective lens to indicate meteoroid velocity (once observations were triangulated with the secondary station). Since this technique only determines the relative timing (velocity) of the meteors and not the arrival times necessary for orbits, sidereal tracking cameras following the relative motion of the sky throughout the night were added alongside the fixed cameras by 1958 [21]. Meteor arrival times were determined by comparing the unguided (fixed pointing) and sidereal tracking guided images [22]. These meteor cameras captured the fireball that lead to the recovery of the Příbram meteorite fragments in 1959, providing the first recovered meteorite with a known heliocentric orbit [23, 24].

The successful recovery of the Příbram chondrite spurred the creation of the Czechoslovak Fireball network—with the goal of meteorite recovery in addition to the previous objectives of meteor observation, trajectory analysis and orbit determination. This new network started operations with five stations in autumn 1963 [25]. These fireball cameras used a single all-sky camera per station instead of multiple narrow angle cameras used by the meteor photography stations; this reduced the workload for the operators manually initiating the night long exposures. The camera and rotating shutter were mounted above a convex mirror to collect all sky imagery. The rotating shutter in the fireball cameras was driven to produce 12.5 breaks per second—slower than the rate used on the previous meteor cameras. The observatories gathered the data required for trajectory triangulation and fall position estimation (trajectory spatial and relative timing data) but employed no method of determining the arrival times of fireballs; the network originally relied on chance fireball observations by the public for arrival times and therefore orbits. Driven sidereal tracking cameras were added to three of the fireball camera sites at a later date to calculate arrival times in the same method used by the original meteor cameras with an accuracy usually within 5 seconds [22].

2.2 Prairie meteorite network

The US Prairie Meteorite Network was established in 1964 with sixteen stations in the Midwest [26]. Each station consisted of four cameras using repurposed rectilinear large format aerial imaging cameras integrated into small buildings with ancillary instrumentation. The Prairie Network observatories also periodically occulted the fireballs (20 times per second) to allow velocity measurement of triangulated events, but departed from the rotating shutter design of previous fireball and meteor cameras. The Prairie observatories utilised a switching shutter constructed from a bistable electromechanical relay attached to a lightweight blade which oscillated in and out of the optical path in the centre of the lens breaking meteor trail images according to a pre-programmed pattern. The pattern embedded into the fireball trail image recorded the fireball's arrival time. The system used repeating sequences which limited the timing precision to a 10.4 second window.

The Prairie systems were also equipped with sky photomultiplier tube (PMT) based photometers alongside each camera to extend the capabilities of the observatory. The photometer controlled the film exposure in response to sky brightness during normal operation, and during extremely bright fireball events, it could reduce the lens aperture and insert a neutral density filter to protect the exposure. The photometer also stamped arrival times (more accurately than the switching shutter timecode) of bright meteors by re-illuminating the data chamber (containing the clock) when meteors brighter than magnitude -4 (fireballs) were detected [26]. The Prairie network recovered the Lost City meteorite with an orbit in 1971 [27] and ceased operation in 1975.

2.3 Meteorite observation and recovery project

The Canadian Meteorite Observation and Recovery Project (MORP) was created after a number of Canadian meteorite falls were recovered in the 1960's, stimulating regional interest in the field. The network started routine operation in 1971 and took a similar approach in observatory design to the Prairie Network, with observatories consisting of five rectilinear cameras housed in a purpose built pentagonal building. The cameras used a rotating shutter with a unique three sector design, consisting of one transparent sector and two neutral density sectors (of densities 2.0 and 5.0) designed to image meteors across a large range of brightnesses [17]. Due their unique design, the rotating shutters in the MORP observatories were driven more slowly than previous designs to produce four dashes per second.

The MORP observatories used innovative PMT based meteor detectors for the precise recording of meteor arrival times. In order to detect fireballs, and reject other common bright transients, two concentric perforated cones were mounted over the PMT. A light source moving at typical fireball speeds would produce a signal in a particular frequency range as the light was periodically blocked and admitted through the holes in the interleaved cones. Signals in this frequency range were detected via electronic filtering, and this commanded the observatory to print the time of the meteor event and advance the film after an appropriate delay. The project operated from 1971 to 1985, recovering the Innisfree [17] meteorite with an orbit in 1977 and produced a sizeable fireball dataset [28–30].

2.4 European fireball network

The Czechoslovak network became the European Fireball Network in 1968 when a number of cameras were installed in southern Germany to work in conjunction with the Czechoslovak cameras. This coverage was again expanded in 1988 when the German cameras were redistributed to cover a larger area including Austria, Belgium and Switzerland [31]. The Czechoslovak part of the network has undergone considerable expansion and modernisation since its inception. The cameras have been upgraded multiple times, first, moving from the manual mirror based all sky cameras to manual large format fisheye lenses providing significantly better precision (angular resolution of approximately one arc minute) and sensitivity. Additional stations with guided cameras for absolute timing were added, and more recently (2003-2008) the manual observatories have been replaced with automated observatories [32]. These contain the same larger format film fisheye imaging configuration but are automated for 32 exposures providing five to seven weeks of autonomous observing, depending on conditions, by way of a magazine equipped film handling system [32]. The cameras monitor observing conditions using precipitation sensors and video camera based star counters. If conditions are favourable, the observatories commence night long exposures and continue to monitor the observing conditions throughout the night (pausing or ending observations as required). The automated observatories are also equipped with PMTs to measure sky brightness during fireball events. The brightness is logged at 500 Hz, (later upgraded to 5000 Hz [7]) producing detailed brightness curves for mass estimation via the photometric method [33]. The automated observatories are networked through a central server and can rapidly alert researchers of the occurrence of bright fireballs. The European Network has recovered a number of meteorites through systematic search campaigns (including Neuschwanstein [34], Košice [35], Žďár nad Sázavou [6] and Stubenberg [6]) and provided orbital or trajectory data for a number of other meteorites found by members of the public in Europe (including Jesenice [36] and Križevci [37]); the network continues to operate to this day. Recently the European Network has also started the transition to digital observatories [6].

2.5 Desert fireball network — initial phase

The excellent searching terrain in the Australian Nullarbor was the motivation for the development of the Australian Desert Fireball Network; the initial phase was conducted using four fireball observatories [10] based on the automated Czech design [32]. The design was modified to deal with the extreme heat of the Australian Outback with the addition of side panels and a retractable sunshield to shade the system during the day, a modified thermal management system, and special high reflectance paint to minimise solar heating. The solar powered observatories were installed on pastoral stations, network connectivity was provided by geostationary satellite data links, and the generous volunteer hosts changed the film magazines as required.

The initial DFN observatories track fireballs well, but are expensive, difficult to install and costly to run and maintain; the £60,000 120kg observatories (Fig. 2) required a truck and three days of work by a small team to install. The systems required monthly film magazine changes were powered by eighteen 80 Watt solar panels. Storage was provided by a small shed of flooded lead acid batteries. Maintenance was complicated by the size and weight of the observatory.

The initial phase of the DFN commenced routine operation in 2005 and produced two meteorites with orbits: Bunburra Rockhole [11, 38] in 2008 and Mason Gully [12, 13] in 2010. This proved the viability of a fireball camera network based in the Australian Outback and laid the groundwork for the expanded digital DFN. Operation of the initial film based observatories ceased in 2015 once the expanded digital network using the observatories described in this work commenced operations.

Fig. 2 DFN large format film based observatory — used in initial phase, prototype digital observatory visible in background

One aspect common to all of the custom engineered observatories used by these previous networks is their high cost and complexity. It would be cost prohibitive and impractical (due to the maintenance requirements) to cover an extremely large area like the Australian Outback with these designs. A substantial reduction in observatory cost and complexity whilst retaining high imaging performance was required to meet the DFN coverage goals.

3 The need for a more practical and cost effective photographic fireball observatory

The meteorite recovery rate of a fireball camera network depends on the size of the coverage area and nature of the meteorite searching terrain. The southern half of the Australian Outback, and the Nullarbor in particular, is excellent terrain for meteorite recovery, so the primary factor influencing the number of meteorite recoveries is the observational capability of the DFN. With nearly ideal night time observing conditions in this region due to low light pollution and minimal cloud cover to interrupt observations, this capability is primarily dependant upon the double station (triangulable) coverage area.

Network coverage depends on the number and spacing of observatory stations which is constrained by observatory imaging capabilities and the logistics of installation and maintenance. The number of stations is directly determined by the costs and maintenance requirements of the fireball camera design. The ideal fireball observatory has a low upfront cost, low ongoing costs, simple installation, infrequent and minimal maintenance and high imaging performance.

Two types of fireball networks exist today: video networks and long exposure photographic networks. Video networks (such as the Southern Ontario All-sky Meteor Camera Network [39], the Slovak Video Meteor Network [40], the Finnish Fireball Network [41], and the French FRIPON network [42]) use analogue or digital video cameras to record meteor trajectories at a high frame rate (usually around 30 frames per second) but at low resolutions (0.3-1 megapixel (MP)). Photographic networks (such as those previously mentioned in Section 2 or the Tajikistan Fireball Network [43]) capture long exposure fireball photographs using high resolution (20+ MP digital or large format film) cameras to record meteor trajectories in a long exposure. The exposures can be up to a few hours in length, so these networks also utilise at least one method of determining meteor arrival times within the long exposure (see Section 4.3).

The video based approach has become popular in recent years due to the increased availability and affordability of sensitive video cameras. Observatories can be constructed from widely available off-the-shelf hardware and software, and the per station cost is low, making them an attractive approach for amateur and collaborative networks. Sensitive video cameras are well suited for recording meteor trajectories to determine geophysical properties by examining ablation and fragmentation and for characterising meteoroid flux and orbital population distributions. However, low resolution cameras do not, generally, record trajectories with sufficient precision to refine fall position distributions to the point where meteorites can be reliably recovered through systematic search campaigns at specific locations (with the exception of more advanced multi camera systems such as [44]). All sky video networks do indicate the general region where meteorites may fall, and these are sometimes then recovered by the public (*cf.* [36, 45, 46]).Video networks also offer limited orbital precision (due to the spatial precision of trajectory observations) which can make matching sporadic fireballs (those not part of a known meteor stream) to parent bodies with high confidence more difficult.

Much higher resolution photographic cameras do offer the spatial precision required to determine fall positions with sufficient accuracy to reliably recover meteorites through systematic search campaigns. Large format film has been traditionally used to achieve spatial precision of approximately one arcminute (limited by film scanning techniques). Long exposure fireball observatories are more complex due to the need to periodically occult the exposure for velocity determination and—traditionally—the need for a separate absolute timing system. Digital photographic cameras now offer the necessary resolution, but are expensive and require custom camera control solutions to function as fireball cameras. For these reasons, the design and construction of high resolution long exposure fireball observatories have typically been out of reach for amateur and collaborative networks.

Reaching the DFN's original goals would be difficult using previous high precision fireball observatories. Modern digital still cameras present an opportunity to develop a smaller, lighter, more power efficient and less costly fireball observatory.

This type of design, constructed around a high resolution consumer digital camera and off-the-shelf components, could satisfy the operational requirements and be constructed for a much lower cost than previously possible.

4 The new automated digital fireball observatory

4.1 Requirements

The main design goals of the new Desert Fireball Network observatory are sufficient spatial and temporal precision to enable meteorite recovery by small teams on foot; the ability to operate reliably and unattended in the Australian Outback for long periods; compatibility with an automated data reduction pipeline; low per-system costs relative to the imaging performance; and simple, fast and inexpensive manufacture, assembly and deployment.

The observatories must be capable of withstanding the extremes of the Australian Outback including temperatures over 50 °C, wind gusts carrying sand and dust in excess of 100 km/hr, thunderstorms bringing occasional torrential rain, and must operate unattended for long periods between servicing and data download visits (ideally at least one year). This requires a robust design with the capability to recover from minor malfunctions such as software or subsystem crashes. Connectivity to enable remote access for administration, troubleshooting and fireball event data download is also desirable.

Small teams on foot in the Outback can cover 2-6 km^2 per week depending on the terrain; trips are usually limited to to around two weeks and 5-12 people due to logistical constraints. This drives the spatial and temporal precision requirements of the network. In order to reduce the uncertainty of the fall position estimate to the point where recovery within these constraints is probable, the trajectory triangulation should be accurate to $\pm$100 metres (triangulation final vector should be accurate to $\pm$ 0.05 degrees) and the mass estimation should be within one order of magnitude. Absolute temporal precision should be 0.01 seconds or better in order to obtain accurate pre-atmospheric entry orbits, enable independent point by point triangulation along the trajectory and allow straightforward alignment with measurements taken by any other instruments. Relative timing precision (for velocity determination and mass estimation) must be significantly more precise.

Camera spacing influences the choice of imaging system; around 100-150 km between sites is a good compromise between coverage density and servicing effort, and suits the spacing of availably installation sites (mostly pastoral stations) in the Outback. A high resolution imaging system is required in order to meet the trajectory precision requirements at this spacing; 36 MP image sensors are readily available in consumer digital cameras and exceed this requirement (even when used with all sky lenses).

In order to deploy a continental scale network, the upfront and ongoing per station costs must be minimised relative to the imaging performance. The upfront costs include materials, manufacturing, assembly and installation while the ongoing costs include maintenance and data connection costs. The move to digital imaging yields both cost reductions compared to film based systems and an automated data reduction capability. The cost and capability of digital imaging has greatly improved in the last decade to the point where commodity consumer cameras have the resolution and sensitivity required to capture fireball imagery with enough precision to produce orbits and recover meteorites. Basing the observatory around off-the-shelf components where possible enables significant cost reductions compared to the highly customised approach of previous observatories.

It is not possible to manually process the large volume of fireball events generated by a continental scale network. To process the huge amount of data generated, the new observatories must be compatible with an automated data reduction pipeline. Consumer digital cameras integrate well into this approach because they allow automatic data download to a computer in a readily accessible format.

The size, weight and power draw of the observatories needed to be reduced compared to previous designs in order to make deployment and observatory maintenance fast and simple. On site maintenance is difficult in the Outback due to the dusty and sometimes harsh conditions. Ideally, the observatory would be small and light enough for spares to be carried on servicing trips. This would allow the observatories to be exchanged in the field and serviced in the lab (for more serious problems), allowing simpler and more time efficient network maintenance.

4.2 Concept design

The proven approach of a long exposure fireball camera with an optical occulter was selected to satisfy the design requirements but implemented with a high resolution digital camera instead of large format film. The long exposures would be limited to around 30 seconds (instead of an entire night) to prevent star trails that hamper lens calibration and astrometry. These 30 second exposures would be collected continuously throughout the night during good observing conditions. A mechanical shutter, of the rotating or switching type, was eliminated early in the design process to reduce the number of expensive and failure prone precision mechanical components. A number of different electro-optic modulators, or shutters, were tested for suitability, and a LC-Tec X-FOS liquid crystal (LC) shutter was selected for it's ease of implementation, proven reliability and long lifetime (http://www.lc-tec.se/products/fast-optical-shutters/). (Liquid crystal displays have been operating in consumer devices for decades.) The LC shutter is driven via a microcontroller through an H-bridge driver. The microcontroller also triggers the camera exposures via the camera's remote release port. The operation of the microcontroller is tightly synchronised with highly precise global navigation satellite service (GNSS) time through a GNSS receiver module. The long exposure images captured by the camera throughout the night are downloaded via an embedded PC using the camera's USB connection; see Fig. 3 for system topology. Images are then automatically analysed by the computer for fireball events before being moved from the solid state drive to the archival disk drives. As a part of the event detection, the observatories communicate with the network's central server via an Internet connection (where available) to corroborate potential fireball events with a preliminary approximate triangulation excluding single station false positives.

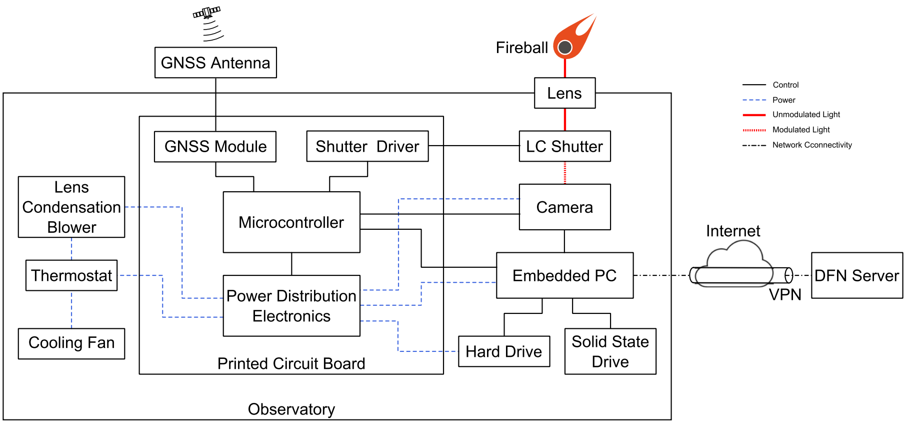

Fig. 3 Digital Desert Fireball Network observatory block diagram showing data and power connections

Rapid development of the fireball observatory was prioritised to get the digital network operational as quickly as possible. A number of cameras and all-sky lenses were tested for suitability. The Samyang 8mm f/3.5 UMC Fish-eye CS II was selected due to the favourable (stereographic) projection and acceptable image quality. The Nikon D800E (later replaced with the D810) digital single lens reflex camera (DSLR) was selected for its weather resistance, high resolution and good noise performance, as well as the ability to control it from a Linux computer via gPhoto2 (http://gphoto.sourceforge.net/). In order to determine the viability of a fireball observatory based around an off-the-shelf consumer camera, four prototypes were rapidly built and deployed for the 2012/13 summer to test the durability of the DSLRs in the hot Australian climate.

The decision to archive all images (instead of only fireball images) was made early in the concept design phase. This eliminated the chance of losing fireball images due to false negatives in the event detection algorithms and allows us to collect a complete wide field optical night sky dataset taken from multiple geographically distinct locations. This dataset is offered to interested researchers for investigation of optical counterparts to radio transients, meteorology, animal behaviour and other fields (contact the authors for access).

To keep the observatory cost low, the primary components (camera, lens, computer, data storage) are commercial off-the-shelf products with small modifications where necessary. The electronics to drive and synchronise the shutter with GNSS time and manage subsystem power are custom designed. The number of moving parts has been minimised to keep costs low and reduce the potential points of failure.

4.3 Fireball timing

A photomultiplier tube is too large and expensive of a solution to fireball timing if the design goals were to be achieved (mostly due to the high voltage power supply required). The flexibility of the microcontroller controlled shutter driver makes it possible to drive the LC shutter to modulate the exposure according to a pattern or sequence. This can be used to embed a unique timecode into the fireball trail recorded by the camera as it travels across the frame during the (30 s) long exposure. This imprinted sequence shows the arrival time (absolute timing) and the velocity information (relative timing) of the meteoroid allowing the calculation of both a fall position and orbit. The ideal sequence is as long as possible while requiring the smallest part of the sequence to be known in order to identify a unique arrival time for the fireball. A longer sequence permits an extended exposure time, reducing the data rate of the camera and wear on the camera's shutter mechanism. This permits less frequent data download and maintenance visits, reducing operating demands and cost. It is desirable to be able to decode the timing from a short part of the sequence because short meteors are more abundant, and statistical analysis of meteoroid populations is another objective of the DFN.

The sequence that optimally satisfies these requirements is a De Bruijn sequence, defined as the shortest possible sequence containing all possible n-element subsequences [47–49]. The microcontroller is precisely synchronised with UTC time via a GNSS receiver to maintain timing precision. The technique eliminates the separate absolute timing subsystem required by most previous designs, reducing, size complexity, and cost. It is the main innovation allowing the new DFN digital fireball observatories to be so compact and cost effective; the approach is detailed in Howie et al. [50]. The Prairie Meteorite Network film cameras also used coded operation of the (mechanical) shutter to record fireball arrival times directly into the fireball image (on film), but this time was only known to within a 10.4 second window which doesn't meet the timing precision requirements of the DFN. For more accurate times the Prairie Network systems depended on the same complex and expensive PMT used in other designs, and this was limited to only bright meteors (fireballs, magnitude -4 and brighter).

The De Bruijn sequence technique used in the DFN observatories encodes absolute and relative timing for all meteors and fireballs that are clearly imaged by the cameras; The absolute timing precision is better than one millisecond and the relative timing is significantly more precise.

Figure 4 shows a good meteorite dropping fireball candidate (DN141129_01) with clearly visible time encoding as observed from the Perenjori DFN station.

The absolute timing precision allows independent triangulation of the fireball data points (two per dash, twenty per second) along the trajectory. This three dimensional point by point triangulation method eschews the straight line assumption used in the traditional methods (intersection of planes [51], least-squares [52] and multiparameter fit [53]).

4.4 Observatory design

In order to rapidly develop the digital fireball observatory, we adopted a concurrent engineering design approach, prototyping early and often. This allowed us to quickly prove the viability of a digital fireball observatory based around commodity imaging hardware and discover the key areas of difficulty early on in the design process.

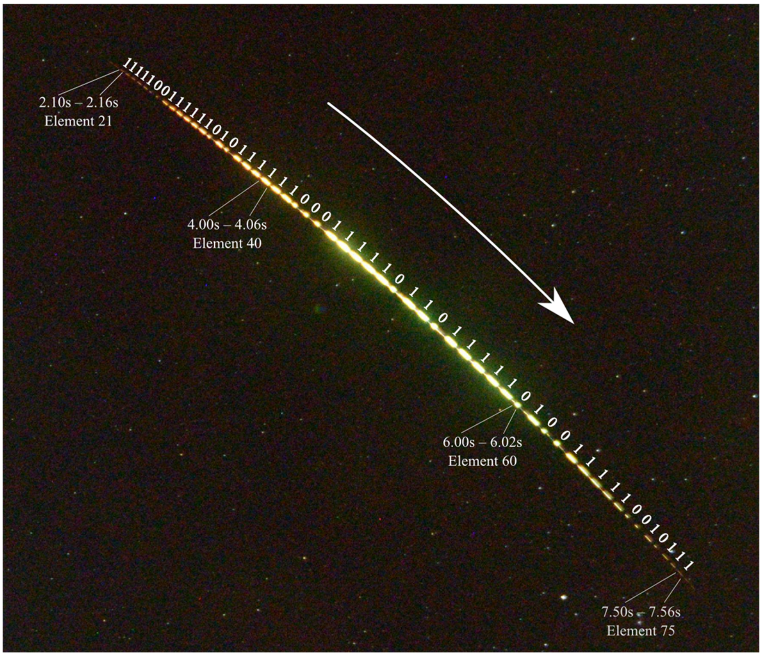

Fig. 4 Enlarged view of DFN fireball event DN141129_01 with de Bruijn sequence time encoding clearly visible. Times relative to exposure start time at 14:31:30 UTC on 29 November 2014

Discovering these problems early on significantly accelerated the design process, and ensured design effort was targeted towards the aspects of the observatory that most required it. Areas where this additional effort was required included the lens environmental sealing and power supply reliability. Care was taken to devise and test simple and creative solutions to design challenges adding minimal cost and complexity before implementing more complex solutions. For example, instead of developing a mechanised lens cover, an inexpensive hydrophobic surface treatment was successfully tested on the prototypes to allow self cleaning of accumulated dust on the lenses during rainfall.

The observatory was designed with manufacture, assembly and maintenance in mind. The number of manual manufacturing steps had to be minimised to construct the significant number of observatories (more than 75) without contracting out the manufacture. This was achieved by modelling the design in a 3D computer aided design (CAD) package and then using affordable and flexible computer aided manufacturing (CAM) techniques including computer numeric control (CNC) laser cutting, CNC water jet cutting, 3D printing and CNC turning for the majority of the manufacturing operations. This computer aided approach allowed us to minimise the number of design revisions by examining the fit and alignment of components in the computer model without waiting for the manufacture of prototype components. Most of the (few) manufacturing steps were performed with these flexible and cost effective manufacturing processes (with minimal or no tooling cost) using the CAD model geometry directly resulting in short lead times. This made rapid design iterations and the short development time possible. Minimal manufacturing processes were performed in-house; the majority of in-house work was semi-skilled assembly performed by casual workers on an as needed basis. This flexibility allowed us to easily respond to design variations and respond to the changing demand as the network roll-out progressed.

Off-the-shelf components were used wherever possible, resulting in significant reductions in up front costs compared to previous fireball observatories (by a factor of about 12). Care was taken to keep the design modular to simplify field and lab based maintenance. The various subassemblies are interconnected using pluggable connectors and, for the most part, can be removed and replaced without removing or disassembling the adjacent subassemblies.

The first observatory prototypes proved the reliability of the selected DSLR and LC shutter in the harsh conditions of the Australian summer as well as the operation of the De Bruijn encoding; the design was revised a number of times adding functionality and refining the existing systems. Care was taken whilst refining the design to ensure complexity was minimised.

The initial observatory prototypes contained a fisheye lens, LC shutter, camera, low powered PC with a system drive, power supplies and a basic circuit with the GNNS module, microcontroller, and shutter driver. The four prototypes were installed at the original film observatory sites (which were still operating at the time). Data was stored on a small dual 3.5 inch drive network attached storage (NAS) device located in the film camera's battery shed and connected via Ethernet. These prototypes successfully proved the concept, and underwent two major revisions to produce the final design: Figs. 5 and 6.

The first major revision added a video camera to provide additional imagery of the fireballs—especially of fragmentation events, increased computing power for image processing, moved the data storage inside the observatory enclosure and integrated more flexible power management.

Lens condensation blowers for the main and video lenses were added to prevent condensation obscuring the images when the temperature of the glass front elements dropped below the dewpoint at night. The design works particularly well because the airflow cools the internal components and then transfers heat to the lenses, reliably defogging them with minimal power usage (compared to lens heaters). Subsystem power management is controlled by the microcontroller and directed via the PC for a flexible system making fine grained power management possible. The subsystems can be powered on and off as required; allowing the solar powered observatory to achieve the desired low power usage. Figure 3 shows the power and control connections between the different observatory subsystems.

The archival data storage consists of two 3.5 inch hard drives (WD Red models with an extended operating temperature range) in a dual drive enclosure connected via USB. Over time the total capacity has increased as larger drives (6 and 8 TB) have become available.

A small number of these second revision prototypes were constructed, and, after testing, the PCB was re-implemented with surface mount components to accelerate production and save board space. A serial level converter was added to allow the PC

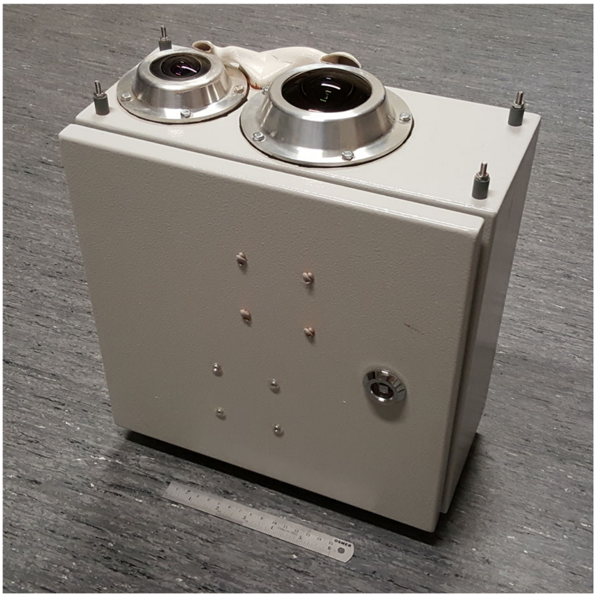

Fig. 5 The exterior of the fireball observatory showing the door, lenses, outer blower ducting and sunshield mounting bolts with a 15 cm ruler for scale

to also receive accurate time information from the GNSS module, and the self reset functionality was also slightly modified. The design as a whole has not changed since this revision, but minor changes have been made to the self reset circuitry and some modifications have been made for production reasons (e.g.: swapping IC packages for more reliable reflow soldering).

The the other components in the observatory have evolved a little over the three years the design has been in use. The camera was upgraded to the Nikon D810 when it was released due to the slightly increased performance and lower cost compared to the D800E. The embedded PC was upgraded to a Commell LE-37D model equipped with USB 3.0 enabling faster image download from the camera, a wider input voltage range, more powerful CPU, additional expansion ports, and a more reliable power connector. The initial observatories had some reliability issues due to power supply problems, but these were eliminated by the PC upgrade, swapping to higher rated solar charge regulators and swapping the DC-DC converter regulating the power to the PC and hard disk drives (HDDs) to a more capable model with a wider input voltage range. The modular design of the observatory allowed most of these changes to be easily retrofitted to the existing systems in the field.

5 Notable design aspects

The observatory has a number of notable features and inventive solutions to problems encountered.

Fig. 6 Fireball observatory internals. Showing (clockwise from top left): video camera and lens, blower ducting, camera and lens (LC shutter inside), embedded PC, observatory management PCB (microcontroller, GNSS module), hard drive enclosure

5.1 3D printed blower ducting

Directing airflow from the lens blower mounted inside the box over the lenses to remove condensation during the night was a significant challenge due to the tight space constraints. A two piece duct was designed in software from the geometry and layout of the box, blower and lenses. The duct is a complex organic shape designed to direct the airflow evenly over the two lenses without sharp turns and provide multiple drain locations for any accumulated water. The part was designed in CAD (see Fig. 7a) and produced on two different 3D printers. This allowed the production of the complicated shape without the significant tooling expense of injection moulding. A simple coat of paint provides UV resistance to the printed plastic part. The final blower and ducting assembly is shown in Fig. 7b.

5.2 Lasercut interlocking stand

Installation of the film observatories was a laborious, time consuming and expensive three day exercise requiring a truck, a large team and pouring of a concrete foundation. A faster and smaller scale installation procedure was required for the rapid deployment of the digital DFN; a semi-permanent support structure would allow this faster deployment and uncomplicated camera relocations if required. The semi-permanent nature of the installation, leaving little to no trace after removal, allowed simpler negotiation of installation sites enabling rapid network deployment.

Fig. 7 Lens condensation blower and ducting. **a** The CAD design showing the complex ducting geometry. **b** The manufactured ducting assembly removed from the observatory with the blower

The stand (Fig. 8) is constructed from interlocking laser cut steel plate which is cut to order with low lead times and machining costs. The interlocking plates fit together like a three dimensional jigsaw puzzle and are affixed with inexpensive steel wedges hammered into specially design slots in the interlocking tabs. This design packs flat and allows rapid installation in approximately thirty minutes. Torsional stability is provided by tensioned wire stays visible in Fig. 1.

5.3 Weather sealed lens flanges and hydrophobic coating

To weatherproof the lenses against the infrequent but sometimes torrential rain, they are sealed into custom designed Aluminium flanges (clearly visible in Fig. 5). The flanges also support the lenses and attached cameras. The flange meets the glass front element of the lens with a thin metal protrusion which is bonded to the glass with a small amount of precisely applied waterproof and flexible silicone sealant. The weather sealing on a few flanges failed initially; the sealant application procedure was modified and no further failures have occurred. The design is versatile and has been adapted to the Samyang 14mm f/2.8 rectilinear and Canon 8-15mm f/4 fisheye zoom lenses for testing and special purpose DFN observatories.

The open flange design does not protect the lens from dust which can lower the contrast and sensitivity of the imaging system. To minimise the accumulation of dirt and ensure water droplets run off the dome shaped front element (instead of evaporating in place leaving a precipitate) the lenses are coated with a consumer hydrophobic surface treatment. This is intended to make the lenses self cleaning; accumulated dust and dirt should be cleaned off when rain droplets bead up and run off the lens. The coating seems to perform as intended, as the lenses remain clean between servicing trips.

Image quality is not affected at all by the flanges making them preferred to protective domes. The weather sealed flanges are also much simpler and less costly than retractable lens covers. They are not susceptible to mechanical or electronic failure helping to increase reliability.

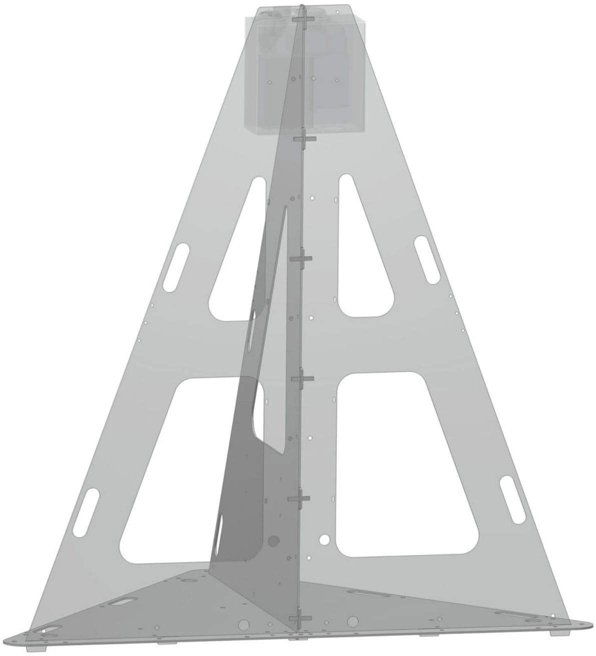

Fig. 8 Stand made from interlocking lasercut steel plates which packs flat and can be assembled on site with steel wedges in about 30 minutes

5.4 Flexible network connectivity

The observatories are networked via an Internet connection where available. This links them to the central server for status reporting and allows event detection to incorporate observations from multiple stations to increase reliability. The observatories support a wide variety of different connection types including: 3G mobile data from two different service providers, Ethernet, WiFi and satellite data. This versatility allows the installation of DFN observatories nearly anywhere, and allows the use of the lowest cost connection on a per-site basis. A virtual private network (VPN) is used to bridge the heterogeneous architecture creating a connection agnostic and seamless network. The majority of the network is connected through 3G mobile data. The connected observatories use a few hundred megabytes of data per month on logs and event detection notifications (which include small image tiles). The observatory is also capable of operating without a network connection; event detection is run on the data from these offline cameras when the hard drives are collected and ingested into the central data store. This mode of operation is used at some remote sites where satellite connections are currently prohibitively expensive.

5.5 Other notable aspects

Some other notable design aspects include the ability to power cycle all of the subsystems including the cameras, PC, HDD's and microcontroller. This allows recovery from occasional software glitches including frozen cameras or dropped USB connections. The observatory enclosure is an off-the-shelf steel hinged enclosure CNC water jet cut to accommodate the observatory fittings. This provides a high quality durable enclosure that meets the requirements without the expense and complication of designing and manufacturing a custom enclosure. CNC cutting makes improvements and new prototypes simple to implement by modifying the CAD software design. Enclosure temperature is regulated by a thermostat controlled cooling fan. (Heating is not necessary at the current observatory sites.) A fixed sunshield mounted on top of the observatory reduces solar heating during the day. The shield is mounted below the protruding lenses and does not obscure the field of view.

5.6 Design for manufacture and assembly

Considerable design effort was focused on the ease of assembly of the observatory to make it possible to produce the design quickly and easily in-house. The manufacturing steps are automated from the CAD design, including the laser cutting of the backplane, HDD support, stand and sunshield; the water jet cutting of the enclosure, gasket, and flange rings; the CNC turning of the lens flanges; and the 3d printing of the blower ducting. The observatory is modular and easy to assemble; the in-house assembly is performed in small batches and takes approximately six hours per observatory.

6 Observatory operation

The observatory is controlled by the embedded PC (Commell LE-37D); flexible scripting allows it to adapt to the operational conditions as required including: position, date, time of day, weather and remaining drive capacity. Online observatories regularly file status reports with the central server and relay fireball event detections, so potentially meteorite dropping fireballs can be analysed before HDD collection. Full size images can be downloaded from online cameras for analysis if required. This is only performed for significant potentially meteorite dropping fireball events due to the high data transfer costs of downloading large raw image files.

The PC is connected to the Atmel ATmega32U4 microcontroller via a USB virtual serial connection (using the LUFA library—http://www.fourwalledcubicle.com/LUFA.php) which controls the observatory subsystems. The PC directs operations with high level commands (e.g.: start camera triggering) that are sent to the microcontroller and then implemented at a low level (e.g.: triggering the DSLR every 30 seconds through the remote release port). This approach avoids tying the observatory to a specific embedded PC; any PC with USB connections for the microcontroller, camera and hard drives would be compatible. Subsystems are only powered by the power distribution electronics when required. This results in substantial power savings for the solar powered observatory as many subsystems are only required for a portion of the day or night (e.g.: camera and video camera at night during good observing conditions, hard drives for 30-60 minutes in the morning while data is archived). The operational and exposure parameters are listed in Table 1.

Table 1 Nominal DFN operational parameters

Parameter	Value	Note:
Exposure Period	30 s	time between exposure starts
Exposure Duration	29 s	shutter open time
Deadtime	1 s (out of every 30 s)	time where shutter is not open
Observing Time	8-14 hours per night	depending on latitude and season
Camera	Nikon D810	older systems use D800/D800E
Sensor Size	35.9 x 24.0 mm	35 mm "full frame"
Image Resolution	36 MP (7360 x 4912)	69 % pixel utilisation, see Fig. 14
Bit Depth	14 bits	
Colour Filter	RGGB Bayer array	
Image Size	45 MB	≈45-75 GB per cloudless night
Image Format	Nikon lossless compressed raw	(.NEF)
Embedded PC	Commell LE-37D	Intel Bay Trail based single board computer
Operating System	Debian GNU/Linux	
Camera Control Library	gPhoto2	
ISO Speed	6400	most stations
Lens Aperture Setting	f/4	most stations
Lens	Samyang 8mm F3.5 Fish-eye CS II	Nikon F mount
Lens Projection	stereographic fisheye	
Image Circle	≈28.7 mm	slight crop at top and bottom of image circle
Field of view	180 degrees	5 % of hemisphere area cropped
Limiting Magnitude, Fireballs	≈0.5 stellar magnitude	
Limiting Magnitude, Stars	≈7.5 stellar magnitude	
Optical Modulator	LC-Tec X-FOS LC Shutter	twisted nematic type liquid crystal shutter
Open state transmittance	36%	
Closed state transmittance	0.1%	
Shutter Operation	de Bruijn time-code	
Shutter Rate	10 dashes per second, $t_e = 100$ ms	10 elements per second sequence rate
Data Point Rate	20 data points per second	dash starts and ends
Particular Sequence	prefer high de Bruijn sequence	$k = 2$ (binary), $n = 9$ (subsequence length)
Encoding	pulse width	$t_0 = 20$ ms, $t_1 = 60$ ms (dash length)

Observations are automatically controlled by local sunset and sunrise times at each site depending on season and location; observations start and stop when the Sun is six degrees below the horizon. Each exposure is modulated by the LC shutter between the lens and the image sensor to encode the arrival time of any fireballs.

The microcontroller precisely synchronises the start and end of the exposure as well as the modulation of the LC shutter with GNSS time to ensure sub-millisecond timing precision. Images are captured in the Nikon raw format. Every fifteen minutes, an image is analysed to determine the quality of observing conditions. Which are quantified using a star counting algorithm comparing the count to a dynamically adjusted threshold that compensates for the presence of the Moon and other bright light sources within the image. Observations are paused in poor conditions to save storage space and shutter actuations (wear on the camera). Analysis of the observing conditions continues at 15 minute intervals, and normal operation is resumed if conditions improve.

The video camera operates at night in parallel with the still camera. One minute segments are saved to the SSD throughout the night and retained on the HDDs where a corresponding event is detected in the still images. The operational parameters for the video camera are shown in Table 2. The video camera observations are not currently incorporated into the automated data pipeline. Expanded video capabilities, including photometry, will be incorporated into the data pipeline in the future.

In the morning, still images are downloaded from the camera's CF card over the USB connection using gPhoto2 and stored on a solid state drive (SSD). Custom automated event detection software then searches the sequence of images for meteor events which are then relayed back to the central server (for online cameras). The server attempts to corroborate the events across multiple observatories by performing a rough triangulation which eliminates most false positives: satellites, aircraft, stray lights. Data is periodically archived from the SSD to the larger HDDs to be collected during servicing and then ingested into the central data store.

When a significant fireball event is detected, the images are processed through the centralised data pipeline—Fig. 9.

Table 2 Nominal DFN video camera operational parameters

Parameter	**Value**	**Note:**
Video camera	Watec WAT-902H2 CCIR ULTIMATE	some older systems using EIA equivalent
Video camera resolution	795 x 582	
Colour Filter	none	panchromatic camera
Bit depth	8 bit, YUV colourspace	
Frame rate	25 fps, interlaced	
Exposure time	1/50 s	
Gain control	auto gain	
Capture card	Commell MPX-885	
Compression	H264 variable bit rate	FFmpeg "ultrafast" preset
Nominal bit rate	$\approx$ 27 Mbps	
Lens	Fujinon FE185C046HA-1	1/2" format 5 MP 185 degree fisheye
Lens aperture setting	f/1.4	
Limiting magnitude	$\approx$2 stellar magnitude	(fireballs and stars)

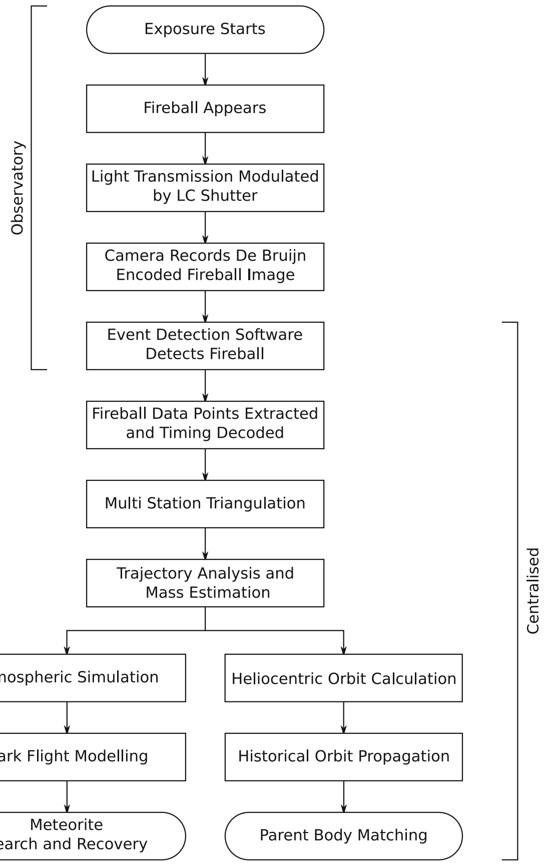

Fig. 9 Stages in the data processing pipeline for a fireball event

7 Data pipeline

When a promising fireball event is flagged by the event detection, the relevant images are downloaded from the cameras or recalled from the data store. Event metadata is tracked throughout the entire pipeline. First, pixel coordinates are selected with timing from the fireball dashes; this is performed manually with a workflow optimised custom software tool (Fig. 10) allowing the points to be selected quickly and reviewed or edited if required. This process takes approximately five minutes per image on average. The luminous trajectory is triangulated using these points and the camera calibration data which characterises the relationship between each observatory's pixel coordinates and the corresponding altitude and azimuth coordinates from each site. This relationship is dependant on the all-sky lens projection, atmospheric refraction, lens distortion (intrinsic parameters) and camera orientation (extrinsic parameters). Calibration is determined by analysing the starfield as imaged by the DLSR. Visible stars are matched to a catalogue iteratively from the centre of the image until the entire field of view is described by a polynomial fit.

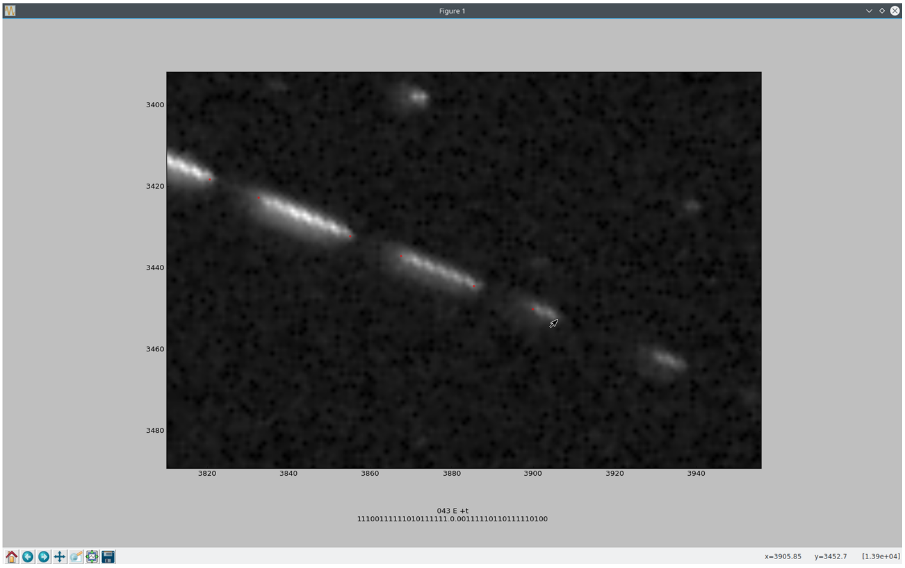

Fig. 10 Fireball data point extraction tool. Times for the data points (in *red*) are automatically calculated from the corresponding de Bruijn sequence element. A partial preview of the sequence, as well as the currently selected element, is displayed to the user at the bottom of the window

Triangulation is currently performed using the least-squares method [52] which makes a straight line assumption, but we are currently developing a independent point by point three dimensional triangulation method that doesn't rely on this assumption. This is only possible due to the absolute timing precision of the observations that is maintained by the GNSS synchronised operation.

The triangulated trajectory is analysed using the dynamic method as described by [18], which uses the observations to estimate meteoroid position, velocity and mass. This method calculates the likely errors based on the uncertainties of the observations and the single body dynamic model. This approach is advantageous because these uncertainties, and in particular the uncertainty of the final mass, can then be factored into the dark flight modelling and incorporated into search and recovery decisions.

The final vector and mass distribution is used to model the dark flight of the meteoroid once it has decelerated to the point where ablation ceases and it is no longer visible to the camera network. The first step of this process is high resolution (3km grid) WRF ARW (http://www.wrf-model.org/index.php) atmospheric modelling of the relevant volume initialised from a regional model incorporating local ground and weather balloon flight data. The fall position distribution is determined by simulation of meteoroid motion through this volume (dark flight) using the Monte Carlo method to incorporate uncertainties (mostly in the mass, final velocity, and the atmospheric model). This fall position distribution is then used to plan the search and recovery of the single meteorite or multiple meteorite fragments. The ideal fireball has a long visible trajectory at a steep angle, a slow final velocity at a low altitude, a final mass estimate of one kilogram or more and a search area in accessible featureless terrain with a stable hard surface [54–56].

The heliocentric meteoroid orbit is calculated from the initial atmospheric entry vector refined in the trajectory analysis using an numerical propagation technique, which can then be back propagated (in time) and possibly matched to a parent body or asteroid family. Where a link can be made and a meteorite recovered, the sample—now of known origin—can be analysed with the proper context; which may, in turn, contribute to new understanding about the formation and current state of the Solar System.

The data processing pipeline, in it's current state, is semi-automated; the individual steps (apart from fireball coordinate extraction) are automated but, for now, the process is manually coordinated. Automation of the image analysis for coordinate extraction is a priority. While the problem is not difficult for the ideal case (a fast, unsaturated fireball in the higher resolution central area of the fisheye lens), it is challenging in many real world cases where the fireball is obstructed, slow or toward the edge of the lens. In the long term, all of the steps and the coordination of the pipeline will be fully automated to produce masses, fall positions and orbits from detected events without manual intervention.

8 Performance

The digital fireball observatory has satisfied the design requirements and enabled the rapid deployment of the digital Australian Desert Fireball Network. The observatories are so cost effective and easy to deploy that the coverage goal has been revised upwards to cover as much good searching terrain as possible within Australia—and this is well under way.

The system has proven to be reliable, suitable for harsh Australian conditions, compatible with a (semi-)automated data pipeline, and easy to install and maintain. The observatories successfully operate for long periods between data download and maintenance trips, but the desired goal of one year between download intervals has not been met yet. The cameras fill two 6TB drives after 8-10 months, but some configuration changes are planned to reduce the filesize of the images, by cropping them to just the region of the sensor used by the fisheye lens. This should extend the download interval to approximately one year when combined with drive upgrades (8 TB drives with suitable temperature ratings are now available and in use at some stations).

The spatial precision of the observatories is approximately one arcminute (down to 5 degrees above the horizon) which is similar to the precision of the previous film based observatories. This allows trajectory triangulation to within several tens of metres. Improvements past this point would do little to refine search areas on the ground due to the dark flight (wind profile) and mass uncertainties. The de Bruijn timecode has performed well: absolute timing precision on the trajectory is better than one millisecond and the techniques has even produced good results for visibly fragmented meteors. The spatial and timing precision achieved more than satisfy the requirements for orbits and ground searches.

The observatories can be fully deployed and commissioned in four hours by two people. The observatories are are small (370x300x150 mm) and light (12 kg). This makes it simple to bring spare observatories on maintenance trips; for more serious problems, they can be exchanged in the field and serviced back in the clean laboratory with more capable equipment. Maintenance in the field and in the lab is made easier by the modular construction. Routine maintenance includes inspection, exchanging hard drives, cleaning the lenses, examining the power systems and connections, operations testing, replacement of the outer blower ducting if required and extracting the occasional spider. The periodic replacement of some parts is planned: the DSLR's mechanical focal plane shutter has a limited lifetime; the outer blower ducting usually lasts for one to two years, and lenses are predicted to degrade at some point from UV exposure and dust storms. Nikon rates the D800/D810 as tested to 200,000 shutter actuations; in practise, the cameras seem to last significantly longer than this: very few have failed to date. One D800 has taken more than 890,000 exposures to date and is still operating, but more time is required to determine the average shutter lifetime under observatory conditions. The cameras can be returned to the manufacturer for a focal plane shutter replacement when required.

A graphical summary of the performance and characteristics of the new digital fireball observatory compared to the previous large format film observatories is presented in Fig. 11.

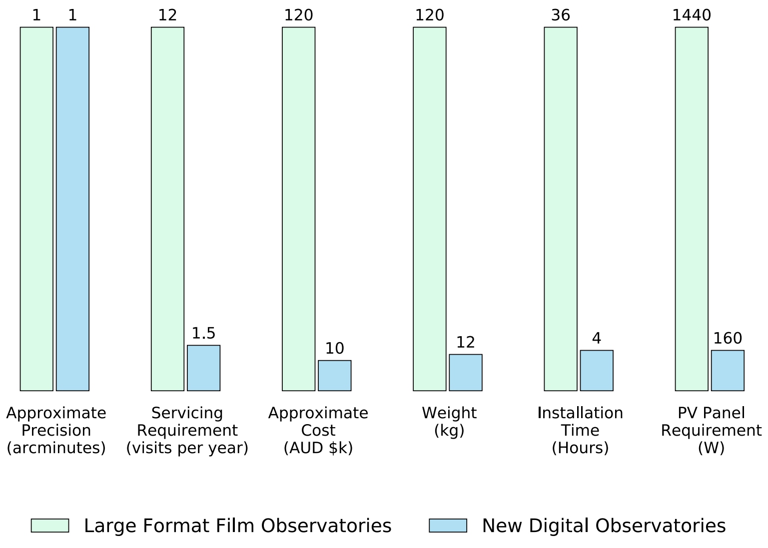

Fig. 11 A comparison of the new digital DFN observatories and the previous film based observatories used in the initial phase

8.1 Network deployment

The first four production observatories were installed in December 2012, and, as of December 2016, the Desert Fireball Network has expanded to 49 stations in three main regions: Western Australia (Wheatbelt and Mid-west), The Nullarbor and South Australia. A new southern Queensland region is also being established. Nominal camera spacing is about 130 km, and the current network coverage (Fig. 12) is $\approx$2.5 million km^2 (approximate double station coverage — where fireball triangulation is possible), which is roughly one third of Australia.

8.2 First recovery — murrili meteorite

The DFN recovered the Murrili Meteorite at the end of 2015 (Fig. 13) using observations from four of the new digital observatories. This is the third meteorite recovered by the DFN and the first using the new digital network. The 6.1 second fireball (Fig. 14) appeared on 27 November 2015 on a steep trajectory into Kati Thanda—Lake Eyre South in South Australia. The heliocentric orbit has also been calculated, and will be presented in a future publication. The 1.7 kg meteorite was located through a systematic search by a small team of three researchers and excavated from

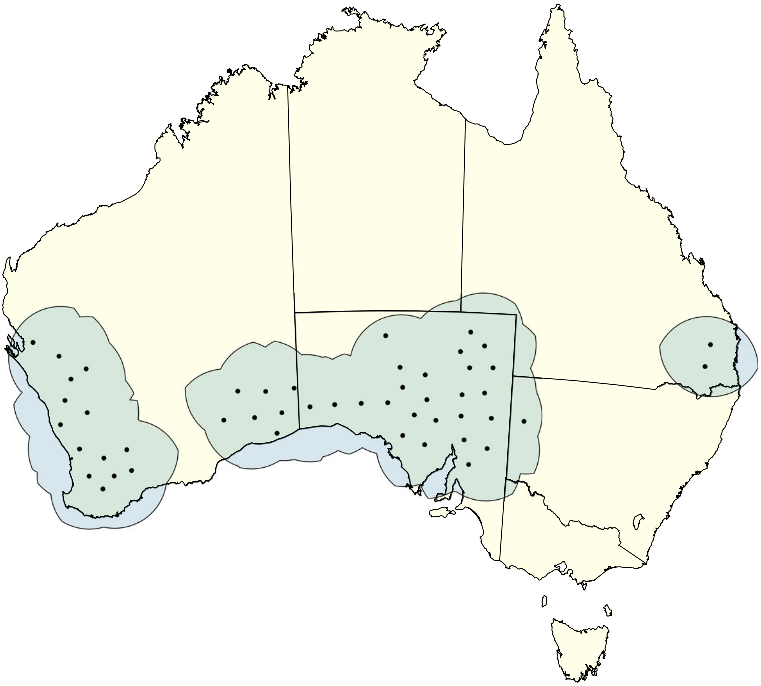

Fig. 12 Current DFN deployment of 49 stations showing approximate double-station coverage (triangulable area)

Fig. 13 The Murrilli Meteorite — the first recovered using the new digital DFN observatories

the thick salt lake mud by hand from a depth of 42 cm. The Arabana People, the local indigenous people, assisted with the recovery and naming of the meteorite. This result demonstrates the success of the digital DFN and the viability of the new observatory design.

Fig. 14 The 6.2 second Murrili Meteorite Fireball, 27 November 2015 10:43:44.50 UTC as observed by the Billa Kalina DFN observatory

9 Future work

Network expansion is ongoing in Australia and internationally through partner networks managed by collaborators. A new version of the camera designed for simple rooftop installation at mains powered sites is under development.

The extreme dynamic range of fireball events pose a problem for all imaging systems. The DFN observatories are well suited for imaging the vast majority of meteorite dropping fireballs, but extremely bright superbolides can saturate large areas of the image sensor, obscuring the trajectory and timing. While events like this are rare (a couple per year at the current network size), they are particularly interesting. Work to improve the dynamic range at both ends of the spectrum is currently under way.

The current (dynamic) mass estimation method [18] does not require brightness, so fireball photometry is not regularly performed. As the data processing pipeline is further developed, fireball photometry will be automatically derived from video camera data using local brightness reference stars to be incorporated in future models.

More than a dozen good meteorite dropping fireball candidates have been observed to date. Fieldwork to recover some of these will be conducted in the future.

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